SU8 3D prisms with ultra small inclined angle for low-insertion-loss fiber/waveguide interconnection

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Abstract: This paper presents a simple method for fabricating SU8 three dimensional (3D) prisms with very small inclined-angles for optical-fiber/planar-waveguide interconnection with low insertion-loss by combining self-filling, molding and nano-lithography processes on plane surface. The prisms possess ultra low 3D inclined angle of 0.6° and a small surface roughness of 3.5 nm. It is demonstrated that the transmission efficiency of SOI waveguides improved about 4.6 times at the presence of SU8 prisms with a coupling loss of 11 dB per taper and radiation loss of 2.4 dB per taper.

OCIS codes: (130.0130) Integrated optics; (130.5460) Polymer waveguides.

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1. Introduction

Fabrication of 3D microstructures (lenses, waveguides, etc.) is very important in optical MEMS and biochip systems. However the dramatically shrunk optical components in micro- and nanoscale result in the desire of interconnection from micro-, nano world into large world [1]. Current methods for light coupling from micro world (for example, optical fibers) into nano world (for instance, waveguide) employed either direct butt end coupling [2], end fire [3], or V-groove [4], not only complicated in fabrication but also contributing alignment-sensitive losses which limit the applications. Vertical couplings based on grating or prisms were employed to reduce insertion loss [5,6], however the couplings were very sensitive to the gap, incident angle, and the selections of prism materials were also very limited.

To overcome those limitations, polymer devices were developed in the past decade with the advantages of low cost, easy fabrication, compatible to MEMS process, and biocompatibility [7]. SU8 (MicroChem Corp., USA) is a negative photoresist widely used in microsystems and nano lighthography. For its high mechanical and chemical strengths, transparent properties in wavelengths above 400 nm, SU8 can be applied to fabricate components for optical devices [8–10]. SU8 is also one of the promising materials for 3D structures fabricated by index matching inclined UV-photolithography technique in water [11] or in Glycerol [8,12]; gray mask [13,14]; or exposure through glass substrate [15]. These methods can be used to fabricate structures of mirrors, lenses with large inclined angles from 19° to 90° where precision is not very critical. However for some applications like taper waveguides, small inclined angles (gradual changes in waveguide height) and smooth surfaces are necessary for minimizing propagation losses. With multidose EBeam lithography, some oblique structures of SU8 and other polymers were successfully fabricated [16] which had inclined angles of 6.1° and above, however, the slopped surfaces of those structures were not flat due to stepped exposure process. Therefore this stepped exposure technology is not suitable for fabricating a 3D taper that requires smooth sloped surface. On the other hand, SU8 3D taper couplers [17] were fabricated as the interconnectors between fibers and silicon waveguides via an intermediate SiO_2 waveguide coated with a thin SiON layer for high efficient coupling. The addition made the process more complicated. Therefore a simple method to fabricate cheap and efficient couplers for interconnecting fiber and nanoscale planar waveguide is highly desired. Linear adiabatic taper of SU8 is one of possible solutions with sizes designed for modes matching to fibers at one side and nanoscale planar waveguide

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at the other side for reduced coupling loss, and smooth gradually sloped (small inclined angle) surfaces for reduced radiation (low loss propagation). In addition, the coupling is more efficient because the refraction index (RI) of SU8, 1.67, is close to that of silica, 1.45. This taper will promise increasing transmission efficiencies. With staircase approximation for a linear adiabatic tapered waveguide structure, theoretical calculation showed transmission efficiency will increase from 70% to nearly 100% for taper angles reduce from 1° to 0° [18]. We choose inclined angles from 0.6° to 1.3° in our interconnectors to carry out low radiation loss and reasonable length for integrating other optic components.

This paper demonstrates a new simple method to fabricate SU8 3D prisms which have small inclined angle down to 0.6° and smooth and flat surfaces. The fabrication process for a SU8 3D prism is consisting of spinning or filling SU8 resist for obtaining SU8 vertically tapering wedge and a standard photo- or EBeam-lithography step for SU8 side tapering shape. The method was applied to fabricate SU8 3D prisms coupled with the waveguides earlier fabricated on SOI substrate in micron meter or submicron meter scales. Small angles of 0.6° and 1.3° were successfully made on the SU8 prisms and the width of the prisms can be further precisely tailored into either 200 nm or 60 nm in photo- or EBeam- lithography, respectively.

2. Fabrication process

2.1 Consideration of aluminum mold and teflon-coated glass limiter for low-angle SU8 tapers

A mold as seen in Fig. 1 was prepared to define the accurate inclined angles of SU8 tapers. The mold symmetrically assembles hinges in its center and spacers on the sides. Positions of the hinges and spacers as well as height of the spacer define the wedge's angle as $atan((h-t)/l)$, where h is the height of the spacer, t is the thickness of the silicon sample, and l is the distance between the hinges and spacer. With the assembled mold, a wedge-shape SU8 layer can be accurately formed under a limiter accommodated by the hinges and spacers. The spacers can be designed with various steps to define different wedge angles. With the symmetrical design, the mold can be used to form either one or two inclined wedges. Two symmetrical wedges can be applied for fabrication of SU8 3D prisms at two sides of a SOI waveguide, as will be presented in section 4.

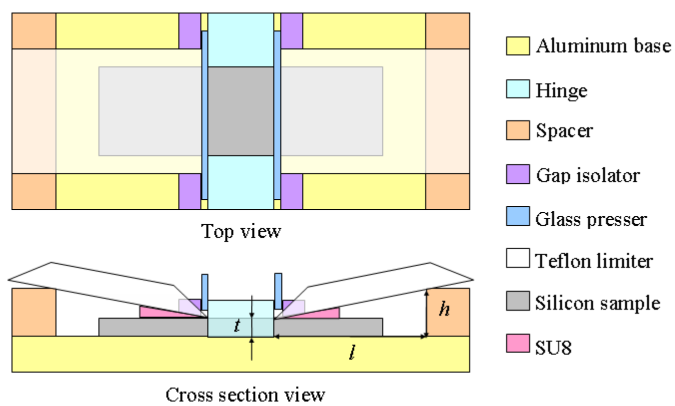

Fig. 1. Schematics of Aluminum mold. It symmetrically assembles hinges, spacers, and limiters.

Aluminum, possessing a very good thermal conductivity (250 W/mK) and low density (2.70 g·cm^{-3}) was selected to be the material for the mold. With designed l of 21 mm and h of 0.7 mm and 1.0 mm, two inclined angles were designated to be 0.6° and 1.3° for t of 500 µm. This mold has three functions including an assembler of components for a desired inclined angle, a stage for vacuum holding in alignment step, and a heat conductor for SU8 baking. Aluminum mold was made by using a computer numerical control machine (MCV-0P,

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LEADWELL, Taiwan) with dimension tolerance of 50 μm, and had backside polished for vacuum holding on photolithography system.

The limiter, employed to confine the top of the wedge, needs to be transparent (for alignment and observation), good thermally conductive (for heat conduction during SU8 baking), and especially hydrophobic to SU8 (for easy limiter demolding). Therefore, a thin Teflon-coated glass is chosen to be the limiter. The Teflon limiter was made by spinning 1% Teflon solution in FC-40 on a glass slide with one well polished edge, then it was baked on a hotplate at 180°C for 25 minutes to remove solvent and further crosslink of Teflon. The Teflon film had a thickness about 100 nm and a contact angle (CA) with DI water and SU8 5 about 111° and 86°, respectively, measured by Contact Angle Measurement System FTA32 (First Ten Angstroms, Inc., USA).

2.2 Fabrication of SU8 tapering wedges with small inclined angle

Two methods including spinning and filling were proposed to fabricate SU8 tapering wedges on silicon substrates.

In the *spinning method* (Fig. 2(a)), a SU8 layer was spin-coated on a cleaned silicon chip and baked at 65°C for 5 minutes. The thickness of the SU8 layer was defined by spinning parameters, including spin speed, time, SU8 viscosity, and its baking temperature as well as baking time. Next, the silicon sample was placed and fixed on the central area of Aluminum mold with a thermal conductive double-sided-adhesive tape (8805, 3M^{TM}, USA). With the Teflon limiter placed on the silicon sample against the hinges on one side by the polished edge and on the spacer by the other side, a small glass slide is inserted into the pressing gap for gently pressing the polished edge (about 10 N/cm^2), and the SU8 layer became a wedge confined by the Teflon limiter. Then Aluminum mold with the silicon sample was baked on a hotplate at 95°C for 10 minutes with Teflon limiter on the top. The hotplate then was turn off to allow the sample cooling into room temperature. After baking and cooling, the solvent in SU8 was removed away, and Teflon limiter can be easy taken off leaving the SU8 surface flat and smooth. The smoothness and flatness of both silicon surface and Teflon limiter edge lead to almost zero thickness of SU8 at the touching position. A typical profile of SU8 tapering wedge is shown in Fig. 2(a) taken by Surface Profiler Dektak^{3}ST (Veeco Instrument, Inc., USA). The SU8 wedge had a minimum representing the low edge - the position where Teflon limiter touched to the silicon sample by pressing, and a maximum representing the high edge with maximal height depending on the inclined angle and initially coated SU8 thickness.

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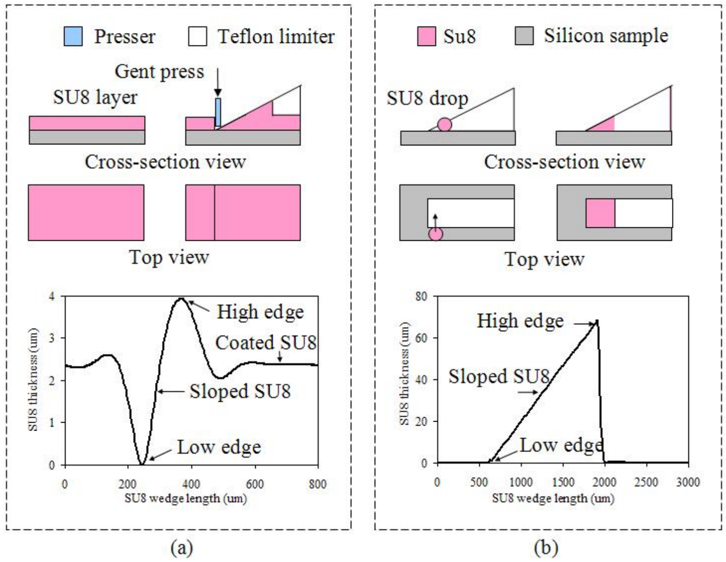

Fig. 2. SU8 wedges formed by (a) spinning and (b) filling methods. Upper parts are schemes of wedge formations, lower parts are profiles of SU8 tapering wedges taken by Surface Profiler Dektak^{3}ST. These SU8 wedges were made with larger inclined angles which were 1.7° and 3.0° in the spinning and filling methods, respectively.

The *filling method* (Fig. 2(b)) is similar to the spinning method except two differences: the SU8 layer is formed by a drop of SU8 solution applied directly on the silicon sample instead of spin coating and the SU8 baking time is much longer due to much thicker SU8 layer formed under Teflon limiter. After a bare silicon sample was placed on Aluminum mold, Teflon limiter was placed on the silicon sample and the spacer as in the spinning method. With observation under optical microscope of an aligner, a 2 μL drop of SU8 5 was applied near by the inclined gap between the silicon sample and the low edge of Teflon limiter. SU8 drop was then self-drawn in by capillary force and filled in the inclined gap. Aluminum mold with the silicon sample was then placed on a hotplate at 65°C and heated up slowly to 95°C, and kept there for 4 hrs for SU8 baking. After natural cooling, Teflon limiter was lifted up easily leaving the SU8 top surface flat and smooth. A typical profile of SU8 wedges made with filling method is shown in Fig. 2(b) taken by Surface Profiler Dektak3ST. The SU8 profile was slant with the angle defined by the limiter without any dip or extrusion.

For the side tapering shape of the SU8 wedge, a standard photolithography (on Mask Aligner and UV Exposure System OAI Model 500, Optical Associates Inc., USA) or EBeam lithography (on ELS-7500EX EBeam Writer, ELIONIX, Japan) was carried out. The exposure dose for 5 μm thick SU8 5 layer was 130 mJ/cm^2 in photolithography and 1 μC/cm^2 in EBeam lithography. After exposure, a post exposure bake was carried out on a hotplate at 65°C and 95°C for 10 minutes each and SU8 is developed with SU8 developer for about 1 minute.

3. Results and discussions

Both spinning and filling methods were used to make SU8 3D prisms, and their SEM images are shown in Figs. 3(a) and 3(b). With the inclined angle of 0.6° or 1.3° defined in SU8 wedge formation step, the length was 450 μm defined by the photomask, the height at the high edge of SU8 wedge was obtained as 5 μm or 10 μm, respectively. The low edge can have a certain height or almost zero height depending on the position shift of the photomask away from the edge of SU8 wedge (Figs. 3(a) and 3(b)) or protruding over it (Fig. 3(c)) during photolithography. It can be seen from the SEM images, the slant and side surfaces of SU8 tapers are flat and smooth. The roughness Ra of the slant surface was measured by Veeco

MultiMode AFM (Digital Instrument, USA) of 3.487 nm over an area of 5*5 μm^2 as shown in Fig. 3(d). The very low surface roughness is one of the factors promising low radiation during the light transport inside this inclined structure made by SU8 polymer.

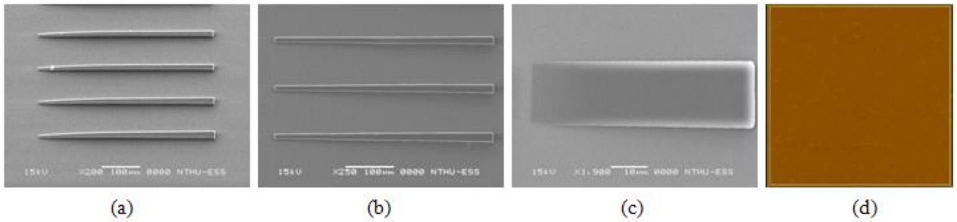

Fig. 3. SEM of 3D SU8 tapers and AFM image of the SU8 slant surface. These tapers were made by spinning (a) and filling (b) methods for the wedge shapes and photolithography for the side shapes. A SU8 taper was made with photomask protruding a bit over the SU8 edge giving almost zero height edge (c). The roughness Ra is about 3.5 nm measured over an area of 5*5 μm^2 (d).

To ensure gradually slopped SU8 taper over its length, the slant SU8 wedge must be made larger than the designed taper length (patterns on the photomask), or the formed shape would not have a gradual slope but a wave profile like as shown in Figs. 2(a) and 2(b). In the spinning method, the height of SU8 taper's high edge is defined by the initial spin-coated thickness and inclined angle. On the other hand, in the filling method the height depends on the slope of Teflon limiter, its width, and the amount of the SU8 drop applied into the gap. With a SU8 5 drop of 2 μL, for an inclined angle of 2°, SU8 can extend to distance of 2 mm from the polished low edge, and at the end position the SU8 thickness is around 70 μm which will pose a longer baking time then that of the spinning method.

To ensure smooth slant surface and zero-height of low edge of SU8 taper, in both methods, it is very important to keep the smoothness of the Teflon limiter edge and the pre-baking time at 95°C. Due to the rectangular shape of the limiter and nature of spinning, the edges of the limiter are hard to get good coverage of Teflon resulting in uncontrollably nonzero edge, as seen in Fig. 4(a). The problem can be solved by immersing the limiter edge in Teflon solution before spinning Teflon, and leaving the limiter leveled for 1-2 minutes before heat treatment at 180°C. The increased SU8 baking times of 20 minutes in the spinning method and of 6 hrs in the filling method reduce further the solvent in SU8 layer facilitating the lifting Teflon limiter without damage the SU8 surface.

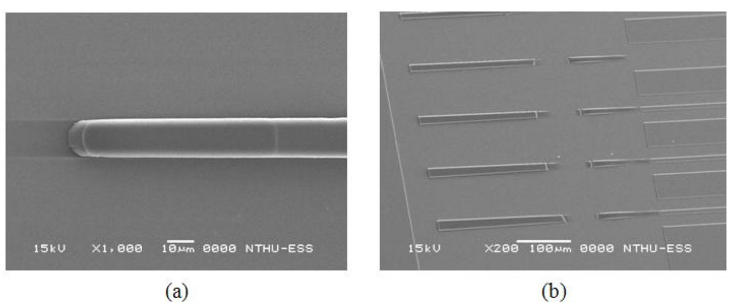

Fig. 4. Some defects may be seen in the fabricated SU8 3D tapers: peeling of SU8 at low edge due to adhesion of SU8 to the uncoated edge of Teflon limiter (a) and uncontrolled broken structures due to the limiters shifted from pressing (b).

When a SU8 prism needs to be formed at some designated position, it is not easy to perform by the spinning method, because the position of the zero-height edge may be formed at a shift position due to improper pressing the Teflon limiter (Fig. 4(b)). This makes the spinning method suitable for freely positioned features, but not for features requiring alignment with earlier fabricated structures. This phenomenon can be avoided in the filling method where the alignment is performed first and the SU8 filling follows later.

Despite of smooth and flat slant surface thank to Teflon limiter, the end facets might not be flat but had rounded corners as seen in Fig. 5(a) due to two main factors: over exposure in lithography and diffraction due to a gap between the flat mask and the SU8 slopped surface [6,19]. As a result to solve these problems, we applied a dose in range of 90-100 mJ/cm^2 for a height of 5-10 μm, and filling Glycerol (having RI of 1.6, near to SU8 RI of 1.67) to compensate the inclined gap. After the adjustment, the end facets of SU8 tapers became smooth and flat, as seen in Fig. 5(b). The Glycerol also helped to enhance the observation during alignment that was difficult due to the inclined gap. The fabricated SU8 tapers have dimensions and positions very close to the designed values with tolerance of 200 nm and 60 nm for photo-lithography and EBeam-lithography, respectively.

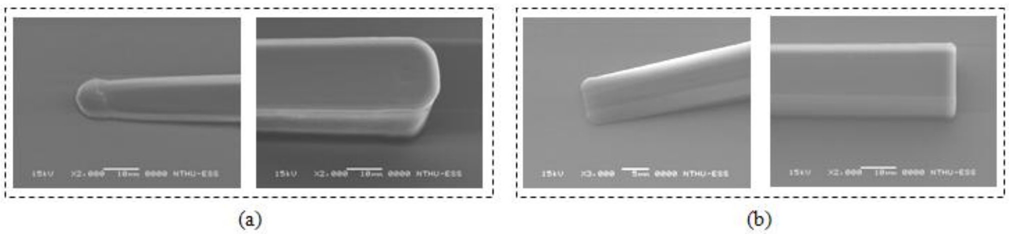

Fig. 5. SU8 tapers with round end facets (a) and flat end facets (b). The improvement was obtained by adjusting exposure dose and filling Glycerol during lithography. Theses SU8 tapers had inclined angles of 1.3°, length of 450 μm. The height difference between two edges is 10 μm.

It is worth to emphasized that from fabrication point of view, the spinning method has two advantages over the filling method: first, the SU8 thickness is small, thus the SU8 baking time is much shorter (20 minutes versus 6 hours); second, the small thickness means small inclined gap (5-10 μm for 0.6-1.3° versus 70 μm) and this makes the alignment easy and reduces diffraction during photolithography. However, the main disadvantage of the spinning method is the poor repeatability due to the uncontrollable pressing step resulting in displacements of the lowest edge or undesirable broken structures. In contrast, the filling method promises consistent results depending on the mold with the fixed elements for accurate angle and self-filling of SU8 drop into the inclined gap thank to the capillary force (SU8 5 has CA of 86° and 14° with Teflon and silicon samples, respectively - measured in our experiments). There is a quite large position tolerance (2 mm) along the side edge of Teflon limiter from the low edge, and a SU8 drop applied at a position within this range can still be drawn into the inclined gap. The filling of SU8, and therefore the maximal height of SU8 wedge depends only on the amount of SU8 drop and the width of the Teflon limiter.

4. Application of the 3D SU8 prism for fiber/silicon waveguides interconnection

A series of biosensors based on photonic crystal (PhC) structures were developed in our Lab, among them were SOI PhC-cavity based biosensors using resonance shift in transmission spectra as a detector for detecting the presence of surrounding chemicals [20]. Thanks to the PhC-cavity based structure, high sensitivity was obtained, however mode and RI mismatching between fibers and SOI waveguide resulted in high insertion loss and low transmission efficiency, typically about 12% by using traditional fiber/waveguide butt end or end fire couplings.

To demonstrate the functionality of the SU8 taper for fiber/waveguides interconnection, we employed 3D SU8 tapers fabricated by filling method as prisms interconnection for optical fiber to SOI straight waveguides, and SOI PhC waveguide fabricated by photolithography and EBeam lithography. SU8 prisms need to have mode matching with both fiber and waveguides by matching the fiber size at one side and waveguide size at the other side. Moreover, with refractive index of 1.67 close to silica's refractive index (1.45), SU8 prisms can have refractive index matching to fiber decently.

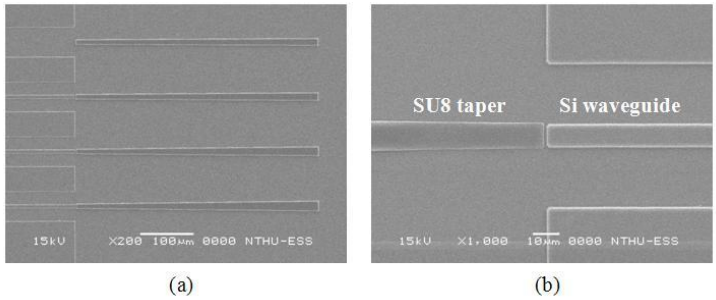

Fig. 6. SEM of a joined waveguides consisting of SOI waveguides and SU8 prisms fabricated by photolithography: (a) overall view of SU8 prisms array, (b) zoomed joining position between SU8 prism and SOI waveguide. The SU8 prisms have a length of 450 μm, cross section are 2*0.34 μm^2 at one side to match with SOI waveguide, and 5*5 μm^2 at the other side to match with fibers. The inclined angle is 0.6°.

Figures 6(a) and 6(b) are SEM images of SOI waveguides integrated with SU8 3D prisms in sequence made by photolithography. The SU8 prisms have a length of 450 μm, thickness at high edge and low edge of 5 μm and 0.34 μm, respectively, and the inclined angle is about 0.6° as designed. The smooth and flat end facets as well as gradually slant surfaces of SU8 prisms promise low coupling loss and low radiation. Figure 7(a) shows experimental transmission spectra of a single SOI straight waveguide (case 1) and of a joined waveguide consisting of a SOI straight waveguide with SU8 3D prisms (case 2). These characterizations were carried out with ASE light source AQ4315A, spectrum analyzer AQ6317C and single-mode lensed fibers with 5 μm diameter tips. Due to unmatching in size (5 μm vs. 0.34 μm) and in refractive index (1.45 vs. 3.45) between optical fibers and SOI waveguide (in case 1) the coupling loss was very high resulting in a low transmission efficiency of 12%. The SU8 prism (in case 2) have matching size (5 μm) and close refractive indexes (1.68 vs. 1.45) to the optical fibers at one side, and have matching size (0.34 μm) to SOI waveguide at other side, therefore the coupling loss was much reduced resulting in a higher transmission efficiency of 55%, a 4.6 times improvement. Suppose the propagation loss over the SOI waveguide (30 μm long) is negligible, the transmission in the 0.6° inclined angle SU8 tapers was 80% [18], the loss caused by the coupling in presence of SU8 3D tapers was 25% (80%–55%), equivalent to 12.5% per taper (about 11 dB), while it was 88% (100%–12%) in case without SU8 prisms. In strict consideration, the coupling loss existed at two positions: fiber - SU8 tapered prism interface and SU8 tapered prism - SOI waveguide interface with the later very sensitive to the gap between SU8 prism and SOI waveguide. According to our simulation results (RSoft Photonics CAD Suite, RSoft Design Group, USA), in the best cases of fabrication where the gap are 60 nm (by EBeam lithography) and 200 nm (by photolithography), the extra loss over the ideal case (with no gap) are 1.8% and 6.2%, respectively. At a gap of 500 nm, the extra loss is as high as 15.3%. To overcome the sensitivity, we have a very simple solution: instead of trying to do the best alignment to have minimized gap, we can align the SU8 taper overlaid the SOI waveguide. This method gives a large tolerance in overlay length for small changes in coupling loss: only about 2.3% difference between cases with no-gap and 1 μm-overlay, with the lower loss in favor for the later, and only 3.6% difference between 1 μm- and 5 μm-overlay [21].

Besides coupling losses, propagation and radiation loss over SU8 inclined taper contribute about 20% in case of 0.6° inclined angle and 40% in case of 1.3° inclined angles [18]. With the SU8 absorption coefficient α of 2 cm^{-1} in estimated wavelength range (1520-1600 nm) [22], the propagation loss over the length x = 2*450 μm is about 16.5% ($1–e^{-\alpha x}$), thus, the radiation is 3.5% (20%–16.5%) for both sides or 1.75% per taper (about 2.4 dB). For inclined

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angle of 1.3 tapers, the radiation is expected to be 23.5% (40%–16.5%) for both sides or 11.75% for one taper (about 10.7 dB).

Similarly, transmission spectra of a SOI PhC waveguide (consisting of PhC structure in its center) and a SOI PhC waveguide integrated with SU8 tapers were shown in Fig. 7(b). It can be seen that the waveform of the two spectra are very close to each other with about 3 times enhancement for SU8 taper waveguides. These characteristics still can be further improved by better alignment during lithography to have a smaller gap, matching shape, matching height between SU8 tapers and SOI waveguide. In addition, since SU8 is transparent in a broad range above 400 nm, the SU8 prisms do not affect to the transmission of SOI waveguides.

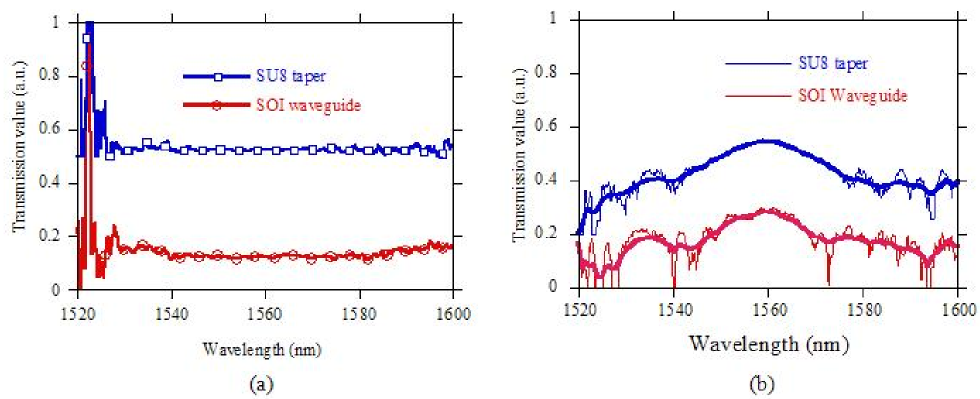

Fig. 7. Experimental transmission spectra of SOI waveguides and a SOI waveguides integrated with SU8 prisms. (a) light propagated over SOI straight waveguides; (b) light propagated over waveguides with PhC structures in the centers. The weighted curves are smoothening.

5. Conclusions

We have demonstrated simple methods to fabricate SU8 3D tapers with small inclined angle (0.6°) and nanoscale tolerance (60 nm) for fiber and planar waveguide interconnection with low insertion loss. The methods combine two steps. First, a wedge-shape layer of SU8 is formed on a silicon substrate by spinning or filling method with hydrophobic Teflon- coated glass limiters to confine SU8 wedge layers of precise inclined angle. Second, a standard photo- or EBeam-lithography is carried out to define the side shape of the tapers. An Aluminum mold integrating the hinges, spacers was fabricated to facilitate the alignment and heat conduction during SU8 baking. The methods allow to fabricate SU8 prisms of very small inclined angles even down to 0.6° and smaller. The filling method was applied to fabricate SU8 3D prisms integrated with waveguides earlier fabricated on SOI substrate. The lengths of the tapers are 450 μm, cross section areas are $0.5*0.34\ \mu m^2$ at one side to couple with the SOI waveguides and $5*5\ \mu m^2$ at the other side to couple with single-mode lensed optical fibers, the inclined angle was 0.6°. With the designed sizes and all surfaces smooth and flat the SU8 prisms provided low insertion loss (about 11 dB/taper) and low radiation (about 2.4 dB/taper), leading to high transmission efficiency. Transmission spectra of a single SOI waveguide and a SOI waveguide with SU8 prisms integrated at input/output were experimentally investigated showing the improvement of 4.6 times in favor for the later. The testing for a SOI PhC based waveguide and its version in join with SU8 3D tapers showed similar waveform.

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